2.8. INVERSE MODELING

Predicting the response of the climate system to anthropogenic emissions of radiatively active atmospheric trace species, such as CO_2 and CH_4, is complicated by important contributions to the budgets of these species from terrestrial biospheric and oceanic processes. In the case of the terrestrial biosphere, interannual variability in parameters such as temperature and precipitation may lead to significant interannual variability in sources of these gases [e.g., *Bousquet et al.*, 2000; *Dlugokencky et al.*, 2001]. Future attempts to manage carbon reservoirs depend critically on the ability to understand and quantify the behavior of terrestrial and oceanic carbon sources and sinks. Two approaches currently being used toward this end are prognostic models of oceanic and terrestrial processes, and inverse models. The latter technique, long used for geophysical problems such as seismology, acoustic tomography, and satellite data retrievals, is an attempt to reconcile predictions from a prognostic model with observations of the trace species in a global network. Early attempts were designed to obtain the interhemispheric gradient of CO_2 fluxes [*Tans et al.*, 1990; *Enting and Mansbridge*, 1991; *Ciais et al.*, 1995a,b; *Bousquet et al.*, 1996; *Law and Simmonds*, 1996]; however, with the expansion of the CO_2 observational network, attempts have been made over recent years to obtain flux distributions over continental scales [e.g., *Fan et al.*, 1998; *Bousquet et al.*, 2000]. Results of the recent TRANSCOM III model intercomparison suggest that the network is currently still too sparse to allow accurate resolution of continental-scale fluxes. The addition of more observation sites, especially over continental and tropical regions, would improve the accuracy of current flux estimates. In addition, it appears that the current generation of transport models needs improvement so that subgrid-scale processes, such as boundary layer transport and convective transport, are accurately represented and do not introduce biases.

Ongoing work by CCGG is focused on development of an operational inverse calculation for flux retrievals at continental scales. The mass balance technique used for these calculations is described in detail by *Bruhwiler et al.* [2000]. A modification to the technique allows the propagation of spatial flux patterns (basis, or response functions, used to quantify the effect of each source region at any particular location) for an arbitrary number of months, resulting in potentially more accurate and stable solutions. In practice, it has been found that response functions need not be calculated for more than about 6 months, and sufficient accuracy may be achieved with only 4 months. This modified version of the mass balance technique may be run using constraints such as semi-empirical ocean flux estimates [*Takahashi et al.*, 1999] and/or terrestrial flux estimates inferred from satellite observations of greenness, e.g., the Carnegie-Ames-Stanford Approach (CASA) model [*Randerson et al.*, 1997]; however, the flux estimates described here were calculated without the use of such prior constraints. The latter strategy allows for the evaluation of flux estimates against the semi-empirical ocean fluxes and satellite-derived estimates of terrestrial fluxes.

Estimates of carbon fluxes were calculated for 11 terrestrial and 11 oceanic regions, corresponding to those used in the TRANSCOM III model intercomparison. The transport model used is Tracer Model Version 3 [TM3, *Heimann*, 1995] with nine vertical levels and a horizontal resolution of 8º latitude by 10º longitude. The model's transport is driven by European Centre for Medium-Range Weather Forecasting (ECMWF) re-analysis wind fields for the years from 1979 through 1993. Inversions for the years after 1993 are typically run using wind fields of all 15 years to define a range of flux estimates. Flux estimates are calculated at monthly intervals so that seasonal cycles may be resolved.

The CO_2 observations used to constrain the inversions are a subset of the GLOBALVIEW-CO_2 data set, consisting of both actual and extended records at 114 network sites distributed globally. The majority of the stations used reflect the behavior of CO_2 in the marine boundary layer. The unresolved variability, or model-data mismatch, is assumed to be 0.5 ppm for oceanic sites and 2.0 ppm for continental sites. The larger error for continental sites is intended to reflect the greater difficulty of modeling continental boundary layer processes.

Carbon flux estimates calculated for the period from 1979 to 1999 show considerable interannual variability in both summertime uptake and spring/autumn respiration. The average uptake over North America for this period is about 0.8 Gt C yr^{-1}, and the net global uptake is partitioned unequally between the land and oceanic regions, with more uptake over land regions. The average uptake by oceans is estimated to be 1.0 Gt C yr^{-1} compared with a net uptake of 2.0 Gt C yr^{-1} found by *Takahashi et al.* [1999]. It is interesting to note that the estimated terrestrial uptake in boreal continental regions is smaller than that suggested by CASA and larger in temperate regions. Whether this bias exists in the CASA model or in the inverse calculations is currently under investigation. Because of the relative sparseness of the observational network in tropical continental and oceanic regions, flux estimates tend be extremely noisy in the tropics and average to zero. This is a reflection of the lack of constraints in these regions. There is a clear need for more observations in these regions.

Figure 2.26 shows estimated terrestrial carbon flux anomalies for 1981 through 1999. For each year, fluxes were estimated using all 15 years of ECMWF windfields. Although this approach was taken because wind fields are not available past 1993, use of multiple years of meteorology for the same flux estimates provides a means to estimate the importance of interannual variability in transport processes. This issue is of special importance, considering that it has been fairly common practice in inverse calculations to use only 1 year of meteorology cyclically. In order to calculate the anomalous carbon fluxes, an average seasonal cycle was subtracted from the time series of total land flux estimates.

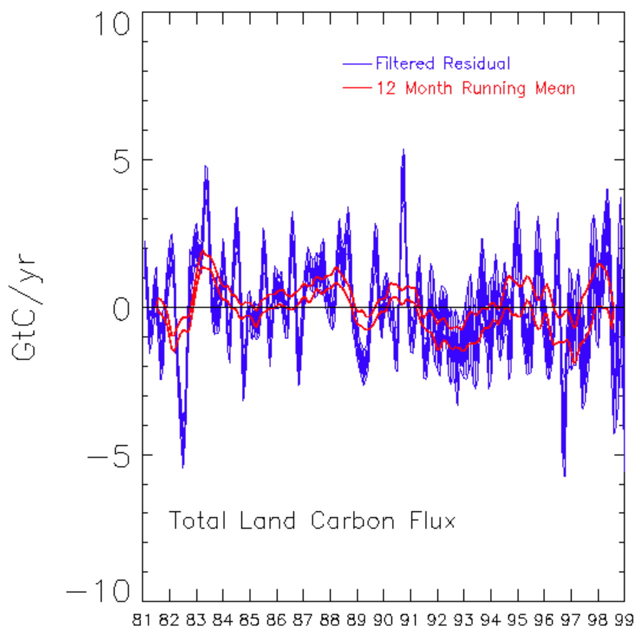

Fig. 2.26. Estimated terrestrial carbon flux anomalies for 1981 through 1999. For each year, fluxes were estimated using all 15 years of ECMWF wind fields. The shaded purple region shows upper and lower limits on the anomalous carbon flux for each month of the inversion calculated by subtraction of an average seasonal cycle. The red lines show upper and lower limits on 12-mo running means of the flux anomalies and reflect annual average behavior of the anomalies.

The upper and lower limits on 12-mo running means of the flux anomalies reflect annual average behavior of the anomalies. Although the running mean anomalies are sensitive to transport differences at a level of about 1 Gt C yr^{-1}, the monthly anomalies may range by as much as about 3 Gt C yr^{-1}. It is therefore highly desirable to use wind fields for the appropriate year when doing these sorts of calculations.

The smoothed flux anomalies in Figure 2.26 show extended periods of positive anomaly (net emission from the terrestrial biosphere) as well as periods of net uptake. Significant positive anomalies occur after the El Niño of 1982-1983 as well as after the 1987-1988 El Niño. The late 1980s are a period of extended net emission from the terrestrial biosphere, while the early 1990s are a period of uptake. A large positive anomaly occurs in 1998 both for the terrestrial biosphere and the oceans (not shown). Comparison to global temperature and precipitation fields (not shown) suggests that the anomalies track trends in these variables.

Plans to improve the current generation of inversions include the use of the NCAR Model of Atmospheric Transport and Chemistry (MATCH), which may be run at higher resolution with more current wind fields from the National Centers for Environmental Prediction (NCEP) re-analysis data set; use of a modified Kalman filter to allow for error propagation; and use of additional observational constraints such as isotopic measurements. In the future, more measurements may become available, which will result in significant improvements in flux estimates.